

Thermal Dileptons as Fireball Thermometer and Chronometer

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Thermal dilepton radiation from the hot fireballs created in high-energy heavy-ion collisions provides unique insights into the properties of the produced medium. We first show how the predictions of hadronic many-body theory for a melting ρ meson, coupled with QGP emission utilizing a modern lattice-QCD based equation of state, yield a quantitative description of dilepton spectra in heavy-ion collisions at the SPS and the RHIC beam energy scan program. We utilize these results to systematically extract the excess yields and their invariant-mass spectral slopes to predict the excitation function of fireball lifetimes and (early) temperatures, respectively. We thereby demonstrate that future measurements of these quantities can yield unprecedented information on basic fireball properties. Specifically, our predictions quantify the relation between the measured and maximal fireball temperatures, and the proportionality of excess yields and total lifetime. This information can serve as a “caloric” curve to search for a first-order QCD phase transition, and to detect non-monotonous lifetime variations possibly related to critical phenomena.

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Collisions of heavy nuclei at high energies enable the creation of hot and dense strongly interacting matter, not unlike the one that filled the Universe during its first few microseconds. While the primordial medium was characterized by a nearly vanishing net baryon density (at baryon chemical potential $\mu_B \simeq 0$), heavy-ion collisions can effectively vary the chemical potential by changing the beam energies, thus facilitating systematic investigations of large parts of the phase diagram of Quantum Chromodynamics (QCD). The yields and transverse-momentum (p_T) spectra of produced hadrons have been widely used to determine the conditions of the fireball at chemical and kinetic freezeout, to infer its properties when the hadrons decouple. Electromagnetic radiation (photons and dileptons), on the other hand, is emitted throughout the evolution of the expanding fireball with negligible final-state interactions and thus, in principle, probes the earlier hotter phases of the medium [1]. In particular, dilepton invariant-mass spectra have long been recognized as the only observable which gives direct access to an in-medium spectral function of the QCD medium, most notably of the ρ meson [2–5]. They also allow for a temperature measurement which is neither distorted by blue-shift effects due to collective expansion (as is the case for p_T spectra of hadrons and photons), nor limited by the hadron formation temperature [6].

Significant excess radiation of dileptons in ultrarelativistic heavy-ion collisions (URHICs), beyond final-state hadron decays, was established at the CERN-SPS program, at collision energies of $\sqrt{s_{NN}} \simeq 20$ GeV [7, 8]. The excess was found to be consistent with thermal radiation from a locally equilibrated fireball [9, 10], with the low-mass spectra requiring substantial medium effects on the ρ line shape. The SPS dilepton program culminated in the high-precision NA60 data, which quantitatively con-

firmed the melting of the ρ resonance and realized the long-sought thermometer at masses $M > 1$ GeV, with $T = 205 \pm 12$ MeV, exceeding the pseudo-critical temperature computed in thermal lattice-QCD (lQCD), $T_{pc} = 150$ –170 MeV [11]. With the spectral shape under control, the magnitude of low-mass excess enabled an unprecedented extraction of the fireball lifetime, $\tau_{FB} = 7 \pm 1$ fm/c.

In the present letter, based on a good description of existing dilepton data from CERES, NA60 and STAR, we show that temperature and lifetime measurements through intermediate- and low-mass dileptons are a quantitative tool to characterize the fireballs formed in heavy-ion collisions. We predict pertinent excitation functions over a large range in center-of-mass energy, $\sqrt{s_{NN}} \simeq 6$ –200 GeV. The motivation for this study is strengthened by several recent developments. First, we show that the implementation of a modern lQCD equation of state (EoS) into the fireball evolution of In-In collisions at SPS recovers an accurate description of the NA60 excess data over the entire mass range, thus superseding earlier results with a first-order transition [12]. Second, the predictions of this framework turn out to agree well with the low-mass dilepton data from the STAR beam-energy scan-I (BES-I) campaign [13, 14], in Au-Au collisions from SPS to top RHIC energies, $\sqrt{s_{NN}} = 19.6, 27, 39, 62.4$ and 200 GeV [15]. Third, a very recent implementation of the in-medium ρ spectral function into coarse-grained UrQMD transport calculations yields excellent agreement with both NA60 and HADES data in Ar-KCl ($\sqrt{s_{NN}} = 2.6$ GeV) reactions [16]; and fourth, several future experiments (CBM, NA60+, NICA, STAR BES-II) plan precision measurements of dilepton spectra in the energy regime of $\sqrt{s_{NN}} \simeq 5$ –20 GeV [17], where the fireball medium is expected to reach maximal baryon density and possibly come close to a critical point in the

QCD phase diagram [18]. Our predictions thus provide a baseline for fundamental, but hitherto undetermined properties of the fireball, allowing for accurate tests of our understanding of these. In turn, marked deviations of upcoming data from the theoretical predictions will help discover new phenomena that induce unexpected structures in the lifetime and/or temperature excitation functions.

Let us recall the basic elements figuring into our calculation of dilepton excess spectra in URHICs. We assume local thermal equilibrium of the fluid elements in an expanding fireball, after a (short) initial equilibration period. The thermal radiation of dileptons is obtained from the differential production rate per unit four-volume and four-momentum [19–21],

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha^2}{3\pi^3} \frac{L(M)}{M^2} \text{Im} \Pi_{\text{EM},\mu}^\mu(M, q) f_B(q_0; T), \quad (1)$$

with $f_B(q_0; T)$: thermal Bose function, $\alpha = \frac{e^2}{4\pi} \simeq \frac{1}{137}$: electromagnetic (EM) coupling constant, $L(M)$: final-state lepton phase space factor, and $M = \sqrt{q_0^2 - \vec{q}^2}$: dilepton invariant mass (q_0 : energy, \vec{q} : three-momentum in the local rest frame of the medium). The EM spectral function, $\text{Im} \Pi_{\text{EM}}$, is well known in the vacuum, being proportional to the cross section for $e^+e^- \rightarrow \text{hadrons}$. In the low-mass region (LMR), $M \leq 1 \text{ GeV}$, it is saturated by the light vector mesons ρ , ω and ϕ , while the intermediate-mass region (IMR), $M \geq 1.5 \text{ GeV}$, is characterized by a continuum of multi-meson states.

Medium effects on the EM spectral function are calculated as follows. In hadronic matter the vector-meson propagators are computed using many-body theory based on effective Lagrangians with parameters constrained by vacuum scattering and resonance decay data [9, 22, 23]. The resulting ρ spectral function strongly broadens and melts in the phase transition region (similar for the ω , which, however, contributes less than 10%; the ϕ is assumed to decouple near T_{pc} and does not produce thermal hadronic emission). For masses $M \geq 1 \text{ GeV}$, we include emission due to multi-pion annihilation using a continuum extracted from vacuum τ -decay data, augmented with medium effects due to chiral mixing [24, 25] in the LMR-IMR transition region ($1 \text{ GeV} \leq M \leq 1.5 \text{ GeV}$) [12]. For QGP emission, we employ an IQCD-motivated emission rate [15] fitted to M -dependent spectral functions above T_{pc} [26, 27] and supplemented by a finite- q dependence taken from perturbative photon rates [28]. The resulting QGP rates are quite similar to the hard-thermal-loop results [29], but with improved low-mass behavior and nontrivial three-momentum dependence. The QGP and in-medium hadronic rates are nearly degenerate at temperatures around $\sim 170 \text{ MeV}$.

To obtain dilepton spectra in URHICs, the rates are integrated over the space-time evolution of the collision. As in our previous work [12, 15, 30, 31], we employ a simplified model in terms of an isentropically

\sqrt{s} (GeV)	6.3	8.8	19.6	62.4	200
z_0 (fm/c)	2.1	1.87	1.41	0.94	0.63
T_{pc} (MeV)	161	163	170	170	170
T_{ch} (MeV)	134	148	160	160	160
μ_B^{ch} (MeV)	460	390	197	62	22
T_{kin} (MeV)	113	113	111	108	104

TABLE I: Excitation function of fireball parameters for the equation of state (T_{pc}), initial (z_0) and chemical/kinetic freezeout (T_{ch} , μ_B^{ch} , T_{kin}) conditions.

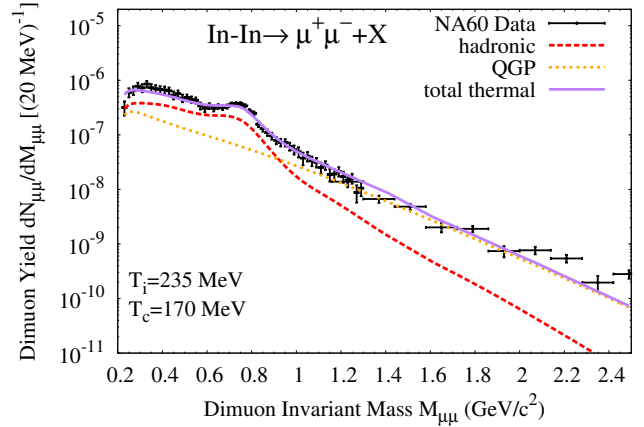


FIG. 1: (Color online) Excess dimuon invariant-mass spectra in In-In ($\sqrt{s_{NN}} = 17.3 \text{ GeV}$) collisions at the SPS. Theoretical calculations (solid line), composed of hadronic radiation (using in-medium ρ and ω spectral functions and multi-pion annihilation with chiral mixing, dashed line) and QGP radiation (using a lattice-QCD inspired rate, dotted line) are compared to NA60 data [8, 41].

expanding thermal fireball. Its radial and elliptic flow are parameterized akin to hydrodynamic models and fitted to observed bulk-particle spectra and elliptic flow (π , K , p) at kinetic freezeout, $T_{\text{kin}} \simeq 100\text{--}120 \text{ MeV}$, and to multistrange hadron observables (e.g., ϕ) at chemical freezeout, $T_{\text{ch}} \simeq 160 \text{ MeV}$. The kinetic freezeout temperatures and radial flow velocities are in accordance with systematic blast-wave analyses of bulk-hadron spectra from SPS, RHIC and LHC [32]. The key link of the fireball expansion to dilepton emission is the underlying EoS, which converts the time-dependent entropy density, $s(\tau) = S/V_{\text{FB}}(\tau) \equiv s(T(\tau), \mu_B(\tau))$ (V_{FB} : fireball volume), into temperature and chemical potential. We employ the EoS constructed in Ref. [33], where a parameterization of the $\mu_B = 0$ IQCD results for the QGP [34, 35] has been matched to a hadron resonance gas (HRG) at $T_{\text{pc}} = 170 \text{ MeV}$, with subsequent hadrochemical freezeout at $T_{\text{ch}} = 160 \text{ MeV}$. We here extend this construction to finite $\mu_B = 3\mu_q$ with guidance from IQCD: The pseudo-critical temperature is reduced as $T_{\text{pc}}(\mu_q) = T_{\text{pc}}[1 - 0.08(\mu_q/T_{\text{pc}})^2]$ [36, 37], and the QGP EoS is modified as $s(\mu_q, T) = s(T)[1 + c(\mu_q/\pi T)^2]$ with

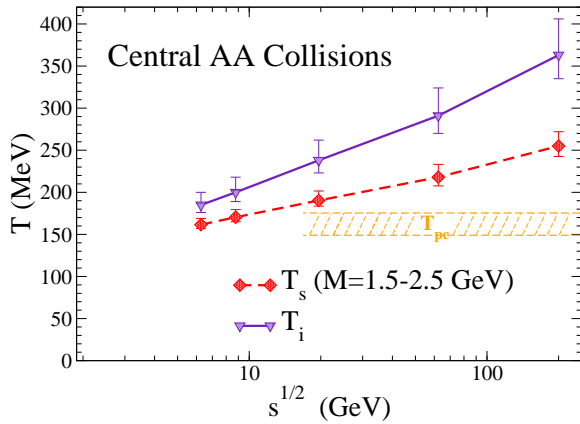


FIG. 2: (Color online) Excitation function of the inverse-slope parameter, T_s , from intermediate-mass dilepton spectra ($M=1.5\text{--}2.5$ GeV, diamonds connected with dashed line) and initial temperature (triangles connected with solid line) in central heavy-ion collisions ($A \simeq 200$). The hatched area schematically indicates the pseudo-critical temperature regime at vanishing (and small) chemical potential as extracted from various quantities computed in lattice QCD [11].

$c \simeq 3$ [38, 39]. For the HRG, we adopt the chemical freeze-out parameters of Ref. [40], cf. Tab. I.

We first test our updated approach with the most precise dilepton data available, the acceptance-corrected NA60 excess dimuons in In-In ($\sqrt{s_{NN}}=17.3$ GeV) [8, 41], cf. Fig. 1. Good agreement with the invariant-mass spectrum is found, which also holds for the q_t dependence, as well as for CERES data [42] (not shown). This confirms our earlier conclusions that the ρ -meson melts around T_{pc} [12], while the IMR is dominated by radiation from above T_{pc} [43–46], mostly as a consequence of a non-perturbative EoS [47]. Furthermore, our predictions for low-mass and q_t spectra of the RHIC BES-I program [15] agree well with STAR dielectron data [13, 14]. Given this robust framework for thermal dilepton radiation in URHICs, we extract in the following the excitation function of two key fireball properties, namely its total lifetime and an average temperature, directly from dilepton observables.

For the temperature determination we utilize the IMR, where medium effects on the EM spectral function are parametrically small, of order T^2/M^2 , providing a stable thermometer: With $\text{Im} \Pi_{EM} \propto M^2$, and in nonrelativistic approximation, one obtains $dR_{II}/dM \propto (MT)^{3/2} \exp(-M/T)$, which is *independent* of the medium’s collective flow, *i.e.*, there are no blue-shift effects. The observed spectra necessarily involve an average over the fireball evolution, but the choice of mass window, $1.5 \text{ GeV} \leq M \leq 2.5 \text{ GeV}$, implies $T \ll M$ and thus enhances the sensitivity to the early high- T phases of the evolution. Since primordial (and pre-equilibrium) contributions are not expected to be of exponential shape (e.g., power law for Drell-Yan), their “contamination” may be

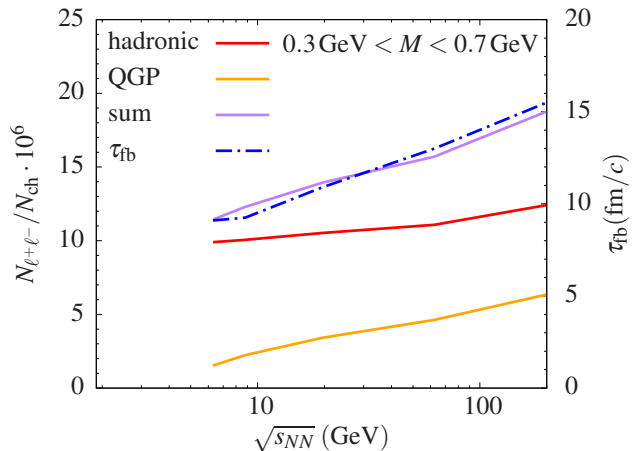


FIG. 3: (Color online) Excitation function of low-mass thermal radiation (“excess spectra”) integrated over the mass range $M=0.3\text{--}0.7$ GeV, as given by QGP (orange line) and in-medium hadronic (red line) contributions and their sum (purple line). The underlying fireball lifetime (dot-dashed line) is given by the right vertical scale.

judged by the fit quality of the exponential ansatz. The inverse slopes, T_s , extracted from the thermal radiation as computed above are displayed in Fig. 2 for collision energies of $\sqrt{s_{NN}}=6\text{--}200$ GeV. We find a smooth dependence ranging from $T \simeq 160$ MeV to 260 MeV. The latter unambiguously demonstrates that a thermalized QGP with temperatures well above the pseudo-critical one has been produced. Our results furthermore quantify that the “measured” average temperature is about 30% below the corresponding initial one (T_i). This gap significantly decreases when lowering the collision energy, to less than 15% at $\sqrt{s_{NN}}=6$ GeV. This is in large part a consequence of the (pseudo-) latent heat in the transition which needs to be burned off in the expansion/cooling. The collision energy range below $\sqrt{s_{NN}}=10$ GeV thus appears to be well suited to map out this transition regime and possibly discover a plateau in the IMR dilepton slopes akin to a “caloric curve”. Another benefit at these energies is the smallness of the open-charm contribution (not included here), so that its subtraction does not create a large systematic error in the thermal-slope measurement. The main theoretical uncertainty in our calculations is associated with the assumed initial longitudinal fireball size, z_0 (which is proportional to the thermalization time): varying the default values quoted in Table I by $\pm 30\%$ induces a $\sim 5\text{--}7\%$ change in the extracted slopes, and a somewhat larger change for the initial temperatures. At given \sqrt{s} , the ratio T_s/T_i is stable within less than 10%.

We finally investigate the relation between the fireball lifetime and the thermal dilepton yields, integrated over a suitable mass window. In Fig. 3 we display the results for a window below the free ρ/ω mass, which is often used to characterize the low-mass excess radiation. It turns out that the integrated thermal excess radiation tracks the total fireball lifetime remarkably well, within

less than 10%. An important reason for this is that, despite the dominantly hadronic contribution, the QGP one is still significant. The latter would be relatively more suppressed when including the ρ/ω peak region. Likewise, the hadronic medium effects are essential to provide sufficient yield in the low-mass region. We have explicitly checked that when hadronic medium effects are neglected, or when the mass window is extended, the proportionality of the excess yield to the lifetime is compromised. With such an accuracy, low-mass dileptons are an excellent tool to detect any “anomalous” variations in the fireball lifetime. A good control over the in-medium spectral shape is essential here, at the level established in the comparison to the NA60 data in Fig. 1.

In summary, we have computed thermal dilepton spectra in heavy-ion collisions over a wide range of collision energies, utilizing in-medium QGP and hadronic emission rates in connection with a lattice-QCD equation of state extrapolated to finite chemical potential. Our description satisfies the benchmark of the high-precision NA60 data at the SPS and is compatible with the recent

results from the RHIC beam-energy scan. Within this framework, we have extracted the excitation function of the low-mass excess radiation and the Lorentz-invariant slope of intermediate-mass spectra. The former turns out to accurately reflect the average fireball lifetime. The latter signals QGP radiation well above the critical one at top RHIC energy, but closely probes the transition region for center-of-mass energies below 10 GeV. Dilepton radiation is thus well suited to provide direct information on the QCD phase boundary in a region where a critical point and an onset of a first-order transition are conjectured.

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